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# High heterotrophic CO<sub>2</sub> emissions from a Malaysian oil palm plantations during dry-season

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**Abstract** Tropical peatlands are currently being rapidly cleared and drained for the establishment of oil palm plantations, which threatens their globally significant carbon sequestration capacity. Large-scale land conversion of tropical peatlands is important in the context of greenhouse gas emission factors and sustainable land management. At present, quantification of carbon dioxide losses from tropical peatlands is limited by our understanding of the relative contribution of heterotrophic and autotrophic respiration to net peat surface CO<sub>2</sub> emissions. In this study we separated heterotrophic and autotrophic components of peat CO<sub>2</sub> losses from two oil palm plantations (one established in ‘2000’ and the other in 1978, then replanted in ‘2006’) using chamber-based emissions sampling along a transect from the rooting to non-rooting zones on a peatland in Selangor, Peninsular Malaysia over the course of 3 months (June–August, 2014). Collar CO<sub>2</sub> measurements were compared with soil

temperature and moisture at site and also accompanied by depth profiles assessing peat C and bulk density. The soil respiration decreased exponentially with distance from the palm trunks with the sharpest decline found for the plantation with the younger palms with overall fluxes of 1341 and 988 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, respectively, at the 2000 and 2006 plantations, respectively. The mean heterotrophic flux was 909 ± SE 136 and 716 ± SE 201 mg m<sup>-2</sup> h<sup>-1</sup> at the 2000 and 2006 plantations, respectively. Autotrophic emissions adjacent to the palm trunks were 845 ± SE 135 and 1558 ± SE 341 mg m<sup>-2</sup> h<sup>-1</sup> at the 2000 and 2006 plantations, respectively. Heterotrophic CO<sub>2</sub> flux was positively related to peat soil moisture, but not temperature. Total peat C stocks were 60 kg m<sup>-2</sup> (down to 1 m depth) and did not vary among plantations of different ages but SOC concentrations declined significantly with depth at both plantations

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but the decline was sharper in the second generation 2006 plantation. The CO<sub>2</sub> flux values reported in this study suggest a potential for very high carbon (C) loss from drained tropical peats during the dry season. This is particularly concerning given that more intense dry periods related to climate change are predicted for SE Asia. Taken together, this study highlights the need for careful management of tropical peatlands, and the vulnerability of their carbon storage capability under conditions of drainage.

## Introduction

Tropical peatlands are estimated to occupy 441,025 km<sup>2</sup> globally, with more than half of the total area (247,778 km<sup>2</sup>) being located in South-East Asia (Page et al. 2011a), and provide the largest long-term sink of terrestrial carbon (Page et al. 2011b). The substantial amount of carbon (C) present in peatlands of the region has been sequestered over millennia. Nevertheless, recent developments which lead to deforestation and drainage of wetlands, for instance for the purpose of establishment of plantations, may be rapidly turning tropical peat environments into the world's largest sources of carbon emissions (Hoijer et al. 2012; Tonks et al. 2017). The growing world demand for palm oil has driven the extensive conversion of peat into agricultural plantations, with 3.1 million ha of peatlands in the region drained for the establishment of plantations, primarily of oil palm and *Acacia* (Lo and Parish 2013). Peatlands are especially attractive as areas for plantation establishment due to the capacity for water retention of organic soils and high nutrient release from decomposing drained peat soils (Corley and Tinker 2003). However, since oil palm trees do not grow well on waterlogged soil due to poor anchorage and anoxic conditions, the establishment of oil palm plantation requires drainage of peat. This greatly increases the risk of high levels of organic matter decomposition, as the presence of oxygen enables the activity of aerobic microorganisms (Husnain et al. 2014).

Total soil respiration ( $R_s$ ) consists of the autotrophic (root-derived;  $R_a$ ) and heterotrophic (non-root derived;  $R_h$ ) components. Heterotrophic respiration involves only the microbial decomposition of soil organic matter (SOM), whereas autotrophic

respiration encompasses root growth and maintenance respiration of living roots, as well as emissions from mycorrhizal fungi (Epron 2009). A major limitation of our ability to understand the consequences of land use change on decomposition processes and CO<sub>2</sub> losses from tropical peatlands, including oil palm plantations, is the lack of separation of autotrophic and heterotrophic respiration components in the majority of studies (Couwenberg et al. 2010). Consequently, a comparison of losses of C between forests and lands utilised in agriculture is often impossible. Additionally, studies which provide estimates of CO<sub>2</sub> emissions from roots on plantations established on tropical peats are sparse. Jauhiainen et al. (2012) estimated that autotrophic fluxes on an *Acacia* plantation on peat range between 115 and 630 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup> constituting 9–26% of total CO<sub>2</sub> emissions, which compares to findings from oil palm plantations in Indonesia where the autotrophic component was between 15 and 30% of total CO<sub>2</sub> emissions (Dariah et al. 2014). In contrast, Melling et al. (2013) attributed 60% of total soil respiration to autotrophic respiration based on a trenching experiment. Hergoualc'h and Verchot (2014) estimate autotrophic emissions from oil palm planted on tropical peat to be around  $0.9 \pm 2.7$  Mg C ha<sup>-1</sup> year<sup>-1</sup>.

It is possible that differences in autotrophic respiration among plantation are in part related to the age of plantations. Indeed, Dariah et al. (2014) found comparable heterotrophic respiration rates between plantations of 6 and 15 years while net and autotrophic CO<sub>2</sub> emissions were considerably higher in the more productive older plantation. Another uncertainty regarding how land use type influences CO<sub>2</sub> soil flux stems from how the lability of the peat material impacts emissions. It is plausible that surface peat consisting of less decomposed organic matter is the largest contributor to soil CO<sub>2</sub> fluxes as deeper peat may be more degraded and therefore produce less CO<sub>2</sub> due to the recalcitrant nature of the remaining material. Indeed, a relationship between CO<sub>2</sub> emissions and peat functional organic chemistry has been shown from undisturbed tropical peatlands (Wright et al. 2013). However, the variation in peat quality with depth and its role in CO<sub>2</sub> emissions from drained peatlands, including oil palm plantations, remains unclear.

In addition to plantation age and peat quality, the CO<sub>2</sub> flux from tropical peats can be influenced by a

range of other environmental factors. For example, Melling et al. (2005) found CO<sub>2</sub> emissions under different land uses were regulated by different environmental factors: relative humidity in secondary forest, soil temperature for sago plantations, and size of water-filled pore spaces for oil palm plantations. CO<sub>2</sub> flux was also influenced by long-term water table depth on an *Acacia* plantation (Jauhiainen et al. 2012). The association between peat temperature and heterotrophic respiration is driven by an exponential increase in enzymatic activity in response to higher temperatures up to c. 45 °C (Luo and Zhou 2006). Waterlogged conditions of peatlands may limit CO<sub>2</sub> emissions by generating anaerobiosis which reduces peat oxygenation, while very dry conditions and water deficit may also restrain microbial respiration (Jauhiainen et al. 2005; Marwanto and Agus 2014). However, to date neither peat temperature nor moisture controls of CO<sub>2</sub> emissions from oil palm plantations are well understood, particularly in the context of in situ fluxes separated into autotrophic and heterotrophic components of emissions (Couwenberg et al. 2010).

Given the knowledge gaps around the impact of oil palm plantations on C storage and losses, this study aims to determine the relative contribution and controls of autotrophic and heterotrophic respiration in two oil palm plantations of different ages. This will be achieved by answering the following specific research questions: (i) what is the relative contribution of autotrophic and heterotrophic respiration to net CO<sub>2</sub> effluxes from an oil palm plantation on tropical peat? (ii) How do peat C stocks, soil moisture and temperature control heterotrophic and autotrophic CO<sub>2</sub> flux of tropical peatlands utilised as oil palm plantations?

## Methods

### Research sites

The study was conducted on an oil palm plantation cultivated on a peatland located in South Selangor, Peninsular Malaysia. The oil palm plantation from which samples were taken contained a total of 43 km<sup>2</sup> and is within the vicinity of Kuala Lumpur International airport (2°44′25.58″, 101°40′29.08″) and South Langat Forest Reserve. This plantation is situated on a much larger peat soil area of mixed land use in South

Selangor of c. 670 km<sup>2</sup>. Within this, approximately 48 km<sup>2</sup> remains as peat swamp forest (albeit highly disturbed). Average annual rainfall in the area is 2419 mm with the dry season normally occurring from May to September (with rainfall dipping to c. 100–150 mm per month) and, to a lesser extent, also December to February. The examined sites were a first-generation oil palm plantation, established in 2000, replacing secondary forest and a second generation plantation, established in 2006 (original conversion from secondary forest in 1978). Immediately prior to plantation establishment, the forest would have been cleared and ditches dug (to a depth of approximately 1.5–2 m) to drain the peatland resulting in a lower water table. These are then retained for the plantation growth. The peat depth at the time of sampling ranged between 1.5 and 2.1 m. On both plantations, four replicate sites were allocated for CO<sub>2</sub> efflux measurements and six for soil sampling. Soil samples were taken at the four CO<sub>2</sub> measurement sites plus at two extra sites. In both plantation generations, oil palm trees were positioned in the standard planting configuration, in a triangular pattern with the distance between tree trunks being approximately 9 m. Each row of trees was arranged with frond piles between rows (where oil palm leaves are discarded) and open harvesting path walkways between trees. The understory surrounding frond piles consisted mostly of ferns with less aboveground biomass in general at the 2006 plantation as compared with the 2000 plantation. However, the sampling areas themselves, within the harvesting path locations had bare soil, with no understory vegetation. The distance between the two plantations was approximately 1 km.

### Measurement campaign

This study was conducted over a 5-month period in 2014, with soil samples taken in April and measurements of CO<sub>2</sub> flux, soil temperature and moisture conducted during the dry season, in the months of June, July and August, over the course of 2–3 days each month. The soil pH was measured only once, in June or July.

### Soil CO<sub>2</sub> flux

Within each plantation, four replicate sites c. 50 m apart were selected at random. At each site, a palm tree

was selected at random. At each tree, seven collars were placed in a straight line at 0.5 m intervals away from the tree trunk, the first one being located 0.5 m and the last one 3.5 m away from the tree. Surface CO<sub>2</sub> measurements across the transect were made to quantify net soil CO<sub>2</sub> fluxes ( $R_s$ ). Since the majority of oil palm root biomass is estimated to be limited to the zone within a 2 m radius to the tree trunk, the CO<sub>2</sub> fluxes at the 3.5 m collar were assumed to be predominately heterotrophic ( $R_h$ ) i.e. with negligible contribution of root respiration to the net soil CO<sub>2</sub> efflux (Dariah et al. 2014). The assumption of no roots at the 3.5 m distance was tested by digging soil pits at the study sites. This verified that there were no oil palm roots at the 3.5 distance supporting the assumption of no autotrophic contribution from oil palm to soil fluxes at this distance. Furthermore, sampling points were selected in areas with no understory vegetation to prevent roots from affecting autotrophic respiration. The autotrophic CO<sub>2</sub> emissions ( $R_a$ ) were calculated by subtracting the flux measured at the 3.5 m collar from the soil respiration ( $R_s$ ) measured at the distances closer to the trunk, following the approach used by Jauhianen et al. (2012) in an *Acacia* plantation on peat soil.

The CO<sub>2</sub> fluxes were measured with a Li-Cor LI-8100A. At sample locations, round plastic collars cut from PVC pipes of the same diameter as the Li-Cor chamber were inserted (c. 4 cm deep) into the peat c. 24 h before measurements. The Li-Cor soil flux chamber was placed onto the collars to collect the CO<sub>2</sub> flux data. The distance from the peat surface to the collar top was taken from inside the collar before each measurement and the corrections in the gas volume within the chamber were made accordingly. One measurement per collar was made every month and each of these lasted 1 min and 30 s.

In parallel with each CO<sub>2</sub> flux measurement, we monitored soil temperature, moisture and water table depth. Moisture and temperature were measured at a depth of around 5–8 cm immediately adjacent to each collar with a Decagon 5TM moisture probe at the time when measurements of CO<sub>2</sub> fluxes were taken. pH values were measured for each collar with an HI 991001 pH probe (Hanna Instruments). Each measurement was taken in close proximity to a collar. The depth of the water table was obtained manually from dipwells which were located at a distance no greater than 10 m from the CO<sub>2</sub> measurement points.

## Soil Organic Carbon measurement

Six soil sampling points were randomly allocated at each plantation, each being within a 10 m radius from the collar transects. Soil samples were extracted with a Russian peat corer (50 cm barrel length, 5.2 cm inner diameter, Eijkelkamp, the Netherlands) at 20 cm intervals down to 1 m. The samples were collected in air-tight plastic bags and placed in a refrigerator on the day of sampling. The storage temperature was between 3 and 6 °C and the samples were kept for a period of maximum 1 month. The samples were subsequently oven-dried at 70 °C to a constant weight and sieved through a 2 mm sieve. Since it was not possible to separate the dead and the living biomass in the peat, plant parts were not removed from the sieved samples, with the exception of large root fragments.

Soil Organic Carbon (SOC) content was measured via loss on ignition (LOI). Around 4–10 g (depending on the sample) of dried soil was placed in a ceramic crucible, weighed and put in the furnace set at 550 °C for 4 h, upon which the sample weight was measured again. The obtained weights of oven-dried and burnt samples were thereafter used for estimation of SOM and SOC content according to the Eq. 1 (Farmer et al. 2014):

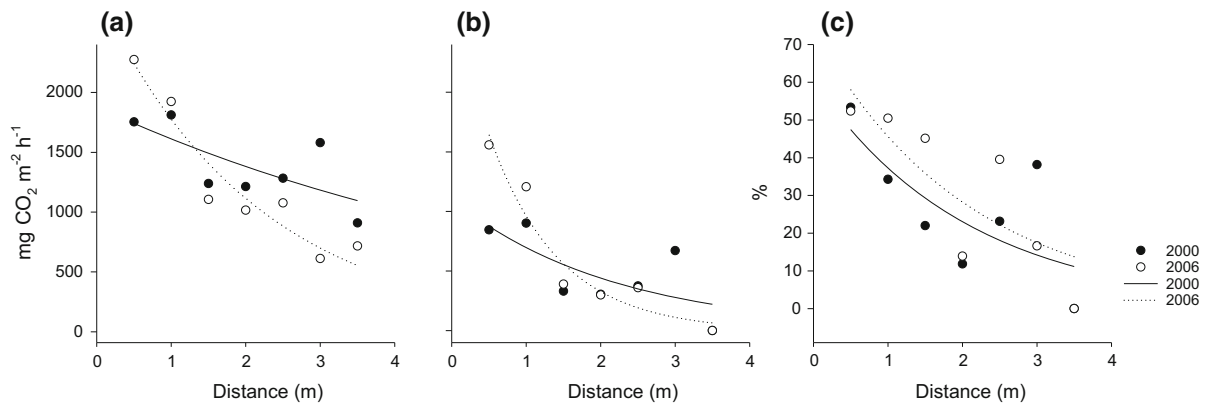
$$\begin{aligned} P_{\text{ash}} &= M_{\text{ash}}/M_{\text{ds}} \times 100 \\ C_{\text{org}} &= (100 - P_{\text{ash}})/R_{\text{OM:C}} \end{aligned} \quad (1)$$

where  $M_{\text{ds}}$  sample dry weight,  $M_{\text{ash}}$  ash weight after combustion,  $P_{\text{ash}}$  sample ash content,  $C_{\text{org}}$  SOC content (%),  $R_{\text{OM:C}}$  conversion factor.

The value of 1.878 was used as the  $R_{\text{OM:C}}$  factor for accurate estimation of SOC content in tropical peats as recommended by Farmer et al. (2014).

## Bulk density

Concurrently, peat dry bulk density (BD) was sampled separately. The samples were collected using fabricated aluminium soil tube samplers (3.5 cm radius and 4.5 cm height), with lid covers. Each sampler was pre-weighed to determine the weight without soil. For sampling, a soil pit of 100 cm depth was dug and samples were taken from the pit wall wall every 20 cm. Soil in the sampler was trimmed to size then closed with lid covers prior to transfer to the laboratory refrigerator. In the laboratory, fresh weight of samples



**Fig. 1** **a** Net  $\text{CO}_2$  flux ( $R_s$ ), **b** Autotrophic ( $R_a$ )  $\text{CO}_2$  flux and **c** relative contribution of  $R_a$  to  $R_s$  along a transect from the palm trunk to outside the canopy at the 2000 and 2006 plantations. Mean  $\pm$  SE are shown;  $n = 84$

was taken before oven-drying. The BD cores were placed in the oven at  $105^\circ\text{C}$  for 1–3 days until a constant weight was achieved. BD values were calculated following Eq. 2 (Dariah et al. 2014):

$$\text{Bulk density (g cm}^{-3}\text{)} = m / V \quad (2)$$

where  $m$  mass of dry soil sample (g),  $V$  volume of sample ( $\text{cm}^3$ ).

#### Statistical analysis and data presentation

All statistical analyses were performed in GenStat version 17. General Linear Models (GLMs) were used to test if  $\text{CO}_2$  fluxes ( $R_s$ ,  $R_a$  and the  $R_a/R_s$  ratio), pH, soil temperature and soil moisture varied with distance from the trunk, months and plantations of different ages using plot as the block effect. Exponential decay functions was used to model the decline in  $R_s$ ,  $R_a$  and the  $R_a/R_s$  ratio with distance from the trunk. Soil respiration was scaled to the appropriate zone (i.e. areas associated with increasing distance from the trunk) using the exponential decay functions.

Linear regression was used to assess environmental conditions (soil temperature and water content, pH, water table level and SOC content) and was related to autotrophic and heterotrophic  $\text{CO}_2$  emissions. The relationship between the heterotrophic  $\text{CO}_2$  flux and water table depth was tested using GLMs with the water table depth as the explanatory variable. The data was visually examined in GenStat for adherence to the normality assumption of GLMs.

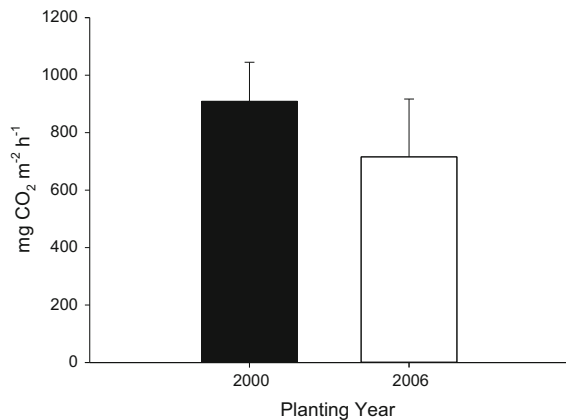
## Results

### $\text{CO}_2$ fluxes

At both the 2000 and the 2006 plantation  $R_s$  was highest adjacent to the palm trunks with  $R_s$  being  $1754 \pm \text{SE } 173$  and  $2274 \pm \text{SE } 233 \text{ mg m}^{-2} \text{ h}^{-1}$  at the 2000 and 2006 plantations, respectively. Fluxes decreased significantly with increasing distance from the tree trunk at both plantations but the decline was sharper at the 2006 plantation (distance  $\times$  plantation interaction:  $F_{(6,167)} = 3.13$ ,  $P < 0.01$ ; Fig. 1a). The decline in the  $R_s$  with distance was described by highly significant exponential decay models ( $F_{(3,13)} = 16.09$ ;  $P < 0.001$ ; Fig. 1a). The overall mean soil respiration ( $R_s$ ) at each of the 2000 and 2006 plantations of was 1341 and 988  $\text{mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ , respectively, when scaled to the relative area equating to the specific distances along the measurement transect.

As expected  $R_a$  declined away from the trunk ( $F_{(6,167)} = 3.26$ ,  $P < 0.01$ ; Fig. 1b) and in parallel with  $R_s$ , the decline was sharper at the more recently re-planted 2006 plantation and followed an exponential decay model ( $F_{(3,13)} = 16.60$ ;  $P < 0.001$ ; Fig. 1b). Autotrophic emissions adjacent to the palm trunks were  $845 \pm \text{SE } 135$  and  $1558 \pm \text{SE } 341 \text{ mg m}^{-2} \text{ h}^{-1}$  at the 2000 and 2006 plantations, respectively. The relative contribution of  $R_a$  to  $R_s$  was 50% at 0.5 m away from the trunk and declined exponentially to 25% 2 m away from the trunk with no significant difference between the 2000 and 2006 plantations ( $F_{(3,13)} = 5.12$ ;  $P < 0.05$ ; Fig. 1c). The





**Fig. 2** Heterotrophic  $\text{CO}_2$  fluxes at two oil palm plantations of different generations. Mean  $\pm$  SE are shown;  $n = 24$

heterotrophic  $\text{CO}_2$  losses measured at 3.5 m distance from the trunk were  $909 \pm \text{SE } 136 \text{ mg m}^{-2} \text{ h}^{-1}$  at the 2000 first generation plantation and were higher than from the more recently replanted 2nd generation 2006 site where  $R_h$  were  $716 \pm \text{SE } 201 \text{ mg m}^{-2} \text{ h}^{-1}$  but this difference was not statistically significant ( $F_{(1,23)} = 0.31$ ,  $P = 0.60$ ; Fig. 2).

The mean soil heterotrophic respiration ( $R_h$ ) across the measurement transect ( $F_{(2, 23)} = 3.09$ ,  $P = 0.08$ ) was lowest in August, the month with the lowest soil temperatures (Fig. 3a–c), while  $R_a$  ( $F_{(2,167)} = 4.82$ ,  $P < 0.01$ ) fluxes was lowest in July which was the month with the lowest soil moisture content (Fig. 3a, b, d).

#### Environmental controls of $\text{CO}_2$ emissions

At the 2000 and 2006 plantations, soil moisture varied significantly between months ( $F_{(2,165)} = 40.81$ ,  $P < 0.001$ ) and so did temperature ( $F_{(2,165)} = 32.05$ ,  $P < 0.001$ ) (Fig. 3b, d). The average volumetric soil moisture content was similar between the two plantations:  $0.20$  and  $0.20 \text{ m}^3 \text{ m}^{-3}$  at the 2000 and 2006 plantations, respectively. Some of the variation in the peat moisture content between months may be explained by the fact that the August measurements, unlike those of June and July, were conducted following a rain event.

A significant interaction between the soil moisture content and site (i.e. 2000 or 2006) ( $F_{(1,44)} = 4.47$ ,  $P = 0.04$ ) (Fig. 4a) suggested that heterotrophic  $\text{CO}_2$  emissions at the 2006 plantation were moisture-

limited. At the 2000 plantation, which had higher  $\text{CO}_2$  emissions overall, there was no clear link between the respiration rates and soil moisture content. The autotrophic flux did not depend on the level of soil moisture ( $F_{(1,20)} = 1.04$ ,  $P = 0.32$ ) (Fig. 4b).

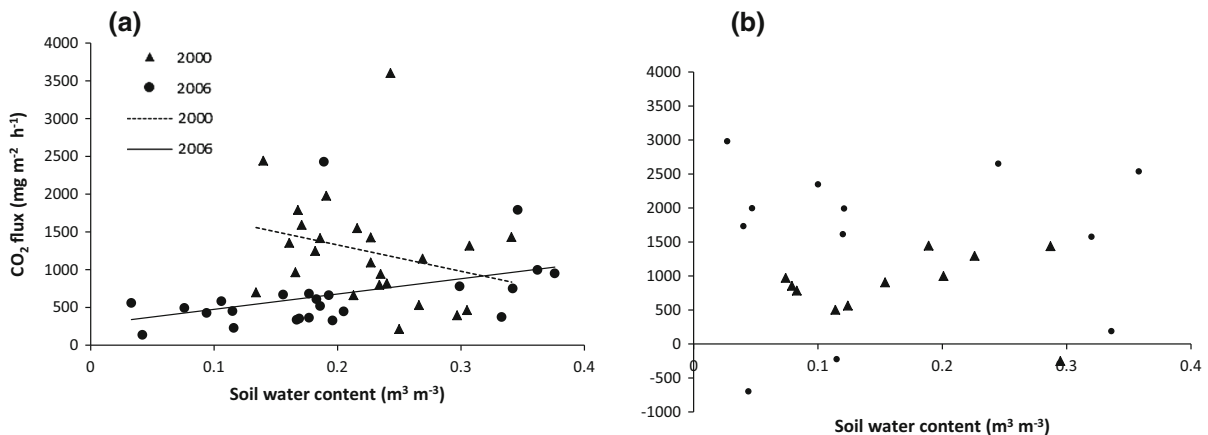
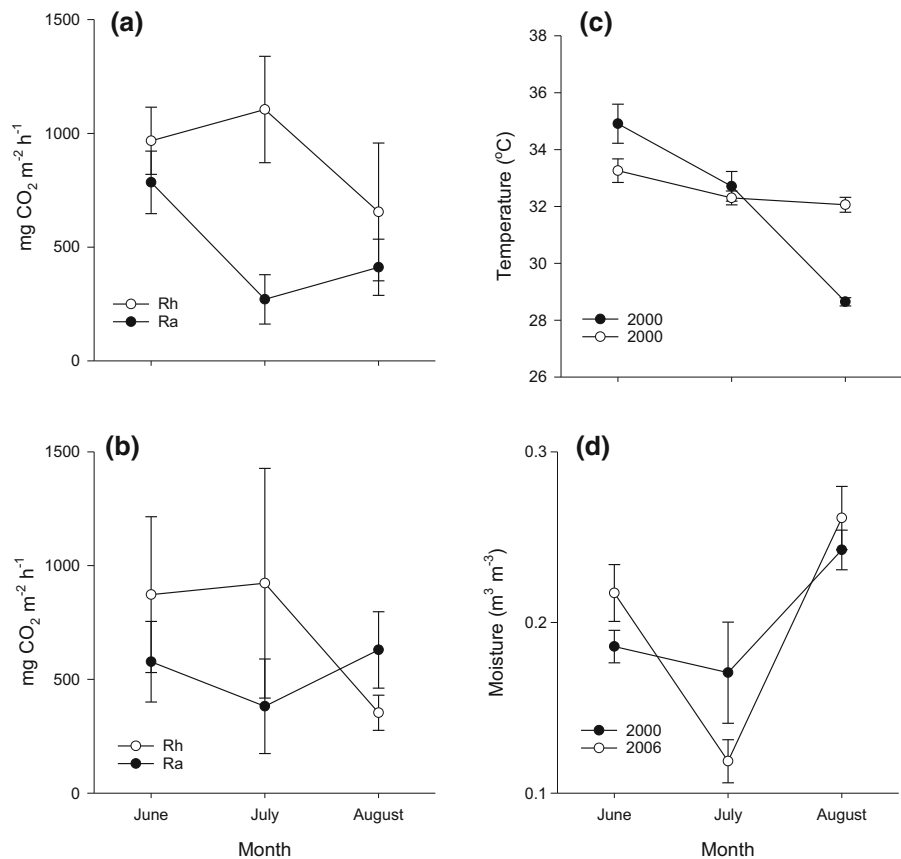
The water table depth (WTD) was measured at four points on the 2000 plantation and at two points on the 2006 age class. At all measurement points, WTD was well below the peat surface and well below Malaysian recommended annual average maxima of  $-40 \text{ cm}$  (Evers et al. 2017) during the entire measurement period, varying between 70 and 120 cm in June and August, which reflected the dry weather conditions that were present during these two months as well as the artificially managed drainage extent. The flux did not depend on the water table level ( $F_{(1,8)} = 0.83$ ,  $P = 0.390$ ,  $r^2 = 0.09$ ). The water table was measured in June and August and, consequently, the  $\text{CO}_2$  flux data that was used in this particular analysis came from June and August only. WTD had no effect on either surface  $\text{CO}_2$  fluxes or peat moisture content of the topsoil during the sampling period ( $F_{(1,8)} = 0.05$ ,  $P = 0.82$ ).

Neither heterotrophic nor autotrophic respiration was influenced by soil temperature ( $F_{(1,44)} = 2.75$ ,  $P = 0.11$ ;  $F_{(1,20)} = 0.84$ ,  $P = 0.37$ ). There was no interaction between soil temperature and site ( $F_{(1,44)} = 2.03$ ,  $P = 0.161$ ). Furthermore, there was no significant relationship between pH and the spatial variation in the heterotrophic  $\text{CO}_2$  emissions averaged by month ( $F_{(1, 12)} = 0.23$ ,  $P = 0.639$ ) at either of the sites.

#### Soil organic carbon content and C stock

Bulk densities were highest at the peat surface apart from at the deepest layer in the 2006 plantation, which was collected from the base of the remaining peat layer (depth  $\times$  plantation interaction:  $F_{(3,47)} = 4.31$ ;  $P < 0.05$ ; Fig. 5a). As expected SOC concentrations declined significantly with depth at both plantations but the decline was sharper in the second generation 2006 plantation (depth  $\times$  plantation:  $F_{(3,47)} = 6.07$ ;  $P < 0.05$ ; Fig. 5b). Overall SOC concentrations were higher in the 2000 than the 2006 plantation at 50 and 37%, respectively. Total peat C stocks were  $60 \text{ kg m}^{-2}$  (down to 1 m depth) and did not vary significantly among the two plantations ( $F_{(1,11)} = 0.68$ ;  $P = 0.4$ ; Fig. 5c).

**Fig. 3** Monthly heterotrophic and autotrophic CO<sub>2</sub> fluxes at the **a** 2000 and **b** 2006 oil palm plantations. The heterotrophic flux corresponds to CO<sub>2</sub> fluxes measured at 3.5 m distance from the trunk. The autotrophic fluxes shown are means across the 0.5–3.0 m measurement transect i.e. does not account for the exponential decay in fluxes with distance and should therefore not be used for comparisons to other sites. Monthly **c** peat temperature and **d** moisture data are shown for the 2000 and 2006 plantations. Mean  $\pm$  SE are shown



**Fig. 4** Relationship between **a** heterotrophic and **b** autotrophic CO<sub>2</sub> flux with soil water content at 2000 and 2006 plantations; significant regression lines are shown. The heterotrophic flux

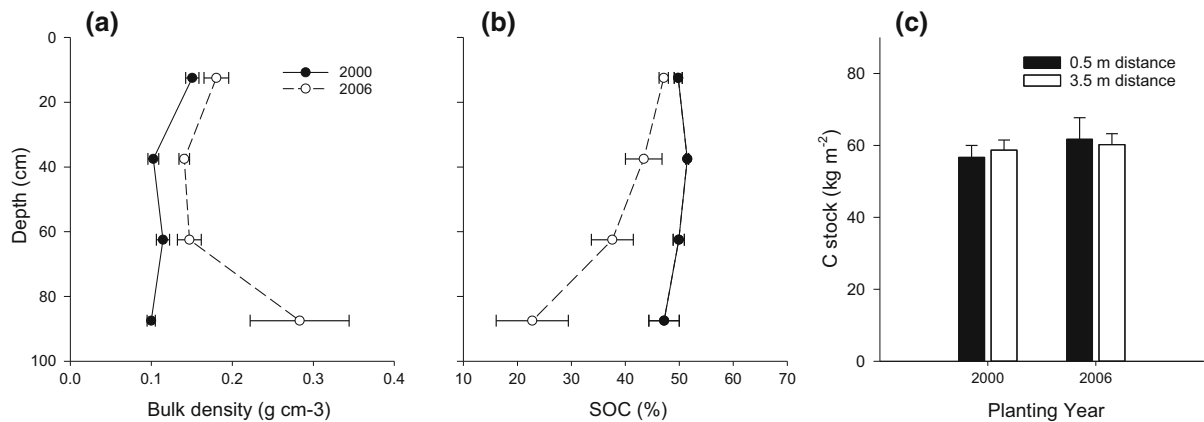
corresponds to CO<sub>2</sub> fluxes measured at 3.5 m distance from the trunk. The autotrophic fluxes shown are from 0.5 m distance from the trunk

## Discussion

The  $R_s$  from both plantations of 117 and 86 Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> for 2000 and 2006 respectively, are at the

higher range of what is reported in the literature for plantations on tropical peat (Jauhianen et al. 2012; Dariah et al. 2014; Husnain et al. 2014). Indeed, our  $R_s$  measured close to the trunks (*c.* 2000 mg m<sup>-2</sup> h<sup>-1</sup>)





**Fig. 5** **a** Soil organic carbon (SOC) content in the peat profile at the 2000 and 2006 oil palm plantations (0.5 and 3.5 m subsites) from depth profiles [0–40 ( $n = 6$ ) and 60–100 ( $n = 9$ ),

respectively]  $n =$  for each variable. Mean  $\pm$  SE are shown; and **b** Carbon stock at the 2000 and 2006 oil palm plantations (0.5 and 3.5 m sub-sites);  $n = 15$  for each subsite

represent some of the highest reported in the literature (Couwenberg et al. 2010). The high emissions are in part likely to be due to our measurements being from day time during the dry season with prevailing high temperatures. To enable comparison with other studies we used our dry season measurement to calculate annual heterotrophic fluxes from our study sites, which were 79 and 65 Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> for the 2000 and 2006 plantation respectively. This is on the higher side of many values previously reported for oil palm plantations on peat e.g. c. 35 Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Dariah et al. 2014), 41 Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Melling et al. 2007),  $19.3 \pm 16.6$  Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Agus et al. 2010), 7 Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> (Melling et al. 2013). Our annual heterotrophic emissions factors are comparable with those of the US Environment Protection Agency, which use an emission factor of 95 Mg CO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup>, based on Hooijer et al. (2012) subsidence assessments. However, care needs to be taken when interpreting the annual fluxes as we expect CO<sub>2</sub> emissions to vary between the wet and the dry season. The CO<sub>2</sub> flux values reported in this study suggest a potential for very high C loss from drained tropical peats during the dry period. This is particularly concerning given that part of the climate projections for SE Asia is more intense dry periods (IPCC 2014) which may further increase CO<sub>2</sub> emissions from drained peatlands.

It is likely that the lower overall SOC (both at the surface and through the peat profile) in the 2006 plantation was caused by long-term high heterotrophic C losses depleting the SOC (Figs. 2, 5b) in line with

Tonks et al. (2017). However, this did not translate into differences in C stocks between the two plantations possibly due the higher bulk densities in the second-generation 2006 plantation. The more dense soil may be due to both mechanical compaction from machinery (Melling et al. 2009) but may also be due to enhanced decomposition as higher bulk densities has been found previously following conversion of peat swamp forest to oil palm plantations (Tonks et al. 2017).

The high contribution of autotrophic respiration to net CO<sub>2</sub> effluxes; 24 and 72% adjacent to the trunk (0.5 m distance) at the 2000 and 2006 plantations, respectively, highlights that it is critical to account for root respiration when estimating C losses from peatlands (Fig. 1). This is particularly important when comparing plantations of different ages, as the relative contribution of autotrophic CO<sub>2</sub> fluxes to net emissions varied considerably among the two plantations as well as spatially with distance from the trunk (Fig. 1; Dariah et al. 2014). The sharp decline with distance from the trunk in the 2006 plantation is likely due to a less extensive root system indicating a lower overall contribution of autotrophic respiration to net emissions at the 2006 plantation. The higher autotrophic flux found close to the younger palms in the 2006 plantation (i.e. 0.5 m distance) was unexpected, given that older oil palms have greater root biomass (Jourdan and Rey 1997; Smith et al. 2012). We speculate that this might be linked to greater NPP and more active root growth in young palm plants or decomposition of old root material from the previous

plantation cycle contributing to the near-palm emissions. The autotrophic respiration was not related to soil moisture or temperature, even though the values of both variables varied substantially between months. This suggests that neither soil moisture nor high temperature limited root respiration.

Moisture was a stronger driver of heterotrophic CO<sub>2</sub> losses than temperature during the measurement period, however, only at the 2006 plantation. This is in line with findings from drained oil palm plantations in Indonesia (Jauhiainen et al. 2005; Marwanto and Agus 2014). Within the range of moisture contents found at the 2006 sites (around 20% volumetric moisture content), greater soil water content increased CO<sub>2</sub> emissions suggesting moisture limitation of decomposition. This may, in part, explain why higher temperatures did not substantially increase emissions, as in contrast to finding on Kalimantan, where peat with moisture contents of 70–80% responded strongly to higher temperatures (Jauhiainen et al. 2014). Although the average soil moisture content did not vary between the two plantations, the short duration of sampling (2–3 days each month) does not represent long-term moisture values, which are likely to be influenced by the variations in canopy coverage and evaporation rates between the old and the new tree stands.

The depth of the water table is considered to affect respiration rates via effects on the water content of the top soil where the SOC mineralisation rate is expected to be the highest (Hirano et al. 2009). In contrast, in this study the water table depth did not impact on the surface peat moisture content or affect the rate of heterotrophic respiration suggesting that the relationship between the water table depth and the microbial respiration was not constant along the whole soil profile or was prevalent to a certain depth only, as has previously been found in temperate and boreal wetlands (Chimner and Cooper 2003; Mäkiranta et al. 2009). However, over long time-scales, a relationship between the water table depth and CO<sub>2</sub> emissions is more likely to be present (Hooijer et al. 2012) and the short duration of this measurement campaign might have prevented the appearance of a clear pattern between the position of the water table and CO<sub>2</sub> emissions. It is plausible that the disconnect between heterotrophic CO<sub>2</sub> emissions and the water table depth shown here, reflects the strong water table draw-down occurring during the dry season. In this case, water

table depth would not a reliable predictor of CO<sub>2</sub> emissions during long periods of drought.

In conclusion, we have identified high heterotrophic CO<sub>2</sub> losses from drained tropical peatlands planted with oil palm. Such high emissions are likely to be sustained as long as the drained conditions are maintained. The low SOC in the second generation oil palm plantation suggests that repetitive plantation cycles and associated soil modification has led to C loss throughout the peat profile. Given the large C deposits in tropical peatlands and the rapid conversion of tropical peatlands to oil palm plantations, these high emissions and changed to C stocks suggests that oil palm plantations can act as hot spots of CO<sub>2</sub> emissions.

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